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Surface plasmon resonance sensor based on photonic crystal fiber filled with gold–silica–gold multilayer nanoshells

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ABSTRACT

We present a surface plasmon resonance sensor based on photonic crystal fiber filled with gold–silica–gold (GSG) multilayer nanoshells for measurement of the refractive index of liquid analyte. The GSG multilayer nanoshells, composed of a silica-coated gold nanosphere surrounded by a gold shell layer, are designed to be the functional material of the sensor because of their attractive optical properties. Two resonant peaks are obtained due to the hybridization of nanosphere plasmon modes and nanoshell plasmon modes. It is demonstrated that the resonant wavelength of the two peaks can be precisely tuned in 560–716 nm and 849–2485 nm, respectively, by varying the structural parameters of the GSG multilayer nanoshells in a compact, sub-200 nm size range. The excellent spectral tunability makes the sensor attractive in a wide range of applications, especially in biosensing in near-infrared region. Furthermore, the influences of the parameters on the performance of the sensor are systematically simulated and discussed. It is observed that the spectral sensitivities of 1894.3 nm/RIU and 3011.4 nm/RIU can be achieved respectively by the two resonant peaks in the sensing range of 1.33–1.38. The existence of two loss peaks also provides the possibility to realize self-reference in the sensing process.

1. Introduction

Surface plasmon resonance (SPR) is an optical phenomenon that an electromagnetic wave is inspired by the interaction of free oscillation electrons and incident photons at the metal–dielectric interface [1]. Compared with traditional sensing techniques, SPR based sensors provide benefits of high sensitivity, real-time rapid detection and label-free sample [2]. Therefore, they have been intensively studied and widely utilized in biotechnology, chemical detection, environmental monitoring, medical diagnostics and many other fields [3–6]. In particular, photonic crystal fiber (PCF) based SPR sensors have attracted great researching interest due to the unique structural characteristics and novel optical properties of PCFs such as design flexibility, large mode area, broad tuning range and so on [7].

The PCF-SPR sensors operate on the basis of the coupling between the leaky core-guided mode and the surface plasmon polaritons (SPP) mode [8]. In recent years, many configurations of PCF-SPR sensors have been studied and reported. B. Gauvreau et al. designed a photonic bandgap fiber based SPR sensor for measuring changes in low refractive index (RI) analyzed and realized a high spectral sensitivity of 13 750 nm/RIU [9]. J. N. Dash et al. presented a side-polished birefringent PCF-SPR sensor by coating indium tin oxide on the polished surface, and a maximum wavelength sensitivity of 17 000 nm/RIU with a resolution of 5.8×10^{-6} RIU is realized [10]. R. Otupiri et al. reported a multi-channel PCF-SPR biosensor by coating different air holes with different materials so that the sensor can operate in both multi-analyte sensing mode and self-reference mode [11]. A. A. Rifat et al. proposed a D-shaped PCF-SPR sensor and used a thin TiO_2 layer as an adhesive layer to tune the resonant wavelength from visible to near-infrared (NIR). A high wavelength sensitivity of 46 000 nm/RIU and a high amplitude sensitivity of 1086 RIU^{-1} are obtained [12].

Gold–silica–gold (GSG) multilayer nanoshells, consisting of a silica-coated gold nanosphere surrounded by a gold shell layer, have generated significant interest due to their unique optical properties, especially the spectral tunability. X. H. Xia et al. reported the synthesis of multilayer nanoshells on the sub-100 nm scale and observed absorption peaks in the visible-NIR spectrum [13]. Y. Hu et al. investigated the spectral properties of GSG multilayer nanoshells by using Mie theory and explained the spectral tunability with a plasmon hybridization model [14]. R. Bardhan et al. described the interaction between the plasmon modes of the gold

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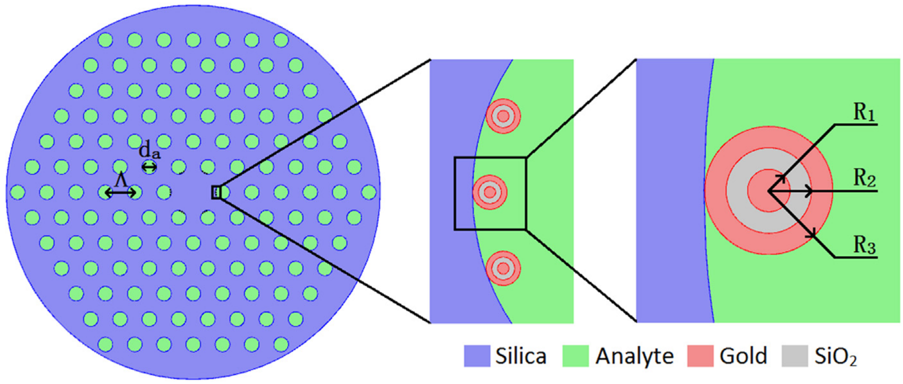

Fig. 1. Cross-section of the proposed PCF-SPR sensor and the structure of the GSG multilayer nanoshells.

nanosphere and the surrounding gold nanoshell in detail [15]. D. J. Wu and X. J. Liu studied the influence of structural parameters and dielectric constant on the optical properties of GSG multilayer nanoshells [16]. The excellent optical properties in NIR spectrum make GSG multilayer nanoshells suitable for biosensing and bioimaging applications.

In this paper, we propose a SPR sensor based on PCF filled with GSG multilayer nanoshells for measurement of the RI of liquid analyte. The full-vector finite element method (FEM) is utilized to numerically simulate the properties of the sensor. The proposed sensor combines the characteristics of PCFs and GSG multilayer nanoshells. The PCF-based structure makes the excitation of plasmon modes much easier while the coupling efficiency between incident light wave and plasmon modes much higher. Two resonant peaks are observed in the spectrum due to the symmetric and antisymmetric coupling between the plasmon modes of the gold nanosphere and the surrounding gold nanoshell. The sensor possesses excellent spectral tunability in visible and NIR regions because of the utilization of GSG multilayer nanoshells, which makes it attractive in many applications, especially in biosensing. It is demonstrated that the resonant wavelength of the two peaks can be precisely tuned in 560–716 nm and 849–2485 nm, respectively, by varying the radius of gold cores, thickness of silica layers and gold shells in a compact, sub-200 nm size range. Furthermore, the influences of the structural parameters on the performance of the sensor are systematically simulated and discussed. The spectral sensitivities of 1894.3 nm/RIU and 3011.4 nm/RIU can be achieved respectively by the two resonant peaks in the sensing range of 1.33–1.38. Meanwhile, the existence of the two peaks also provides the possibility to realize self-reference in the sensing process.

2. Structural design and theoretical modeling

The cross-section of the proposed PCF-SPR sensor and the structure of GSG multilayer nanoshells are shown in Fig. 1. It can be seen that there exist six layers of hexagonal-arranged air holes, all of which are filled with liquid analyte. In order to enhance the coupling efficiency between the leaky core-guided mode and SPP mode while reduce the SPP to SPP coupling [17], only the first layer of air holes are designed to be the sensing channel by filling GSG multilayer nanoshells into them. In [18], Peng et al. demonstrated the feasibility of selectively filling the air holes of the PCFs with liquid. In [19], Lu et al. demonstrated that the performance of the sensor tends to be optimal when the number of the nanoparticles embedded in each air hole of the first layer is three. In [20], Luan et al. demonstrated that the random distribution of the nanomaterials has no effect on the performance of the sensor. In the proposed sensor, the diameter of the air holes and the pitch between two air holes are $d_a = 3.37$ μm and $\Lambda = 6.73$ μm. Meanwhile, in Fig. 1, R_1 is the radius of the gold core, R_2 the radius of the silica-coated core, and R_3 the radius of the GSG multilayer nanoshell. The RI of the background

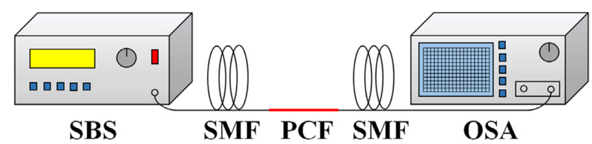

Fig. 2. Schematic of the proposed PCF-SPR sensor system.

material, fused silica, and the silica layer is determined by the Sellmeier equation [21]:

$$n^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}, \tag{1}$$

where λ is the wavelength in microns. For gold properties, data from Johnson and Christy [22] are adapted for the simulation.

The properties of the proposed sensor are numerically simulated and analyzed by utilizing the FEM. The cross section of the sensor is divided into 119 252 triangular sub-domains, in which Maxwell's equations are solved on the basis of system equation and variation principle [23]. The confinement loss of the sensor can be calculated as:

$$\alpha_{loss}\,(dB/m) = \frac{40\pi}{\lambda \cdot ln10} \cdot \mathrm{Im}\left[n_{eff}\right] \approx 8.686 \cdot \frac{2\pi}{\lambda} \cdot \mathrm{Im}\left[n_{eff}\right], \tag{2}$$

where $\mathrm{Im}[n_{eff}]$ is the imaginary part of the effective RI of core-guided mode in the sensor. And the value of $\mathrm{Im}[n_{eff}]$ can be obtained from the simulation results of the FEM-based software COMSOL multiphysics.

The resonant wavelength-based spectral sensitivity of the sensor is defined as:

$$S_\lambda\,(nm/RIU) = \frac{\Delta\lambda_{peak}}{\Delta n_a}, \tag{3}$$

where λ_{peak} is the resonant wavelength of the loss peaks and n_a is the RI of the liquid analyte filled in the air holes. While the amplitude sensitivity of the sensor is defined as:

$$S_A\left(\mathrm{RIU}^{-1}\right) = \frac{\partial\alpha\left(\lambda, n_a\right)}{\partial n_a} \cdot \frac{1}{\alpha\left(\lambda, n_a\right)}, \tag{4}$$

where $\alpha(\lambda,\ n_a)$ is the confinement loss of the core-guided mode, which is related to λ and n_a. Furthermore, the comprehensive property of the sensor can be described by figure of merit (FOM), which is defined as:

$$\mathrm{FOM}\left(\mathrm{RIU}^{-1}\right) = \frac{S_\lambda\,(nm/\mathrm{RIU})}{\mathrm{FWHM}\,(nm)}, \tag{5}$$

where S_λ is the spectral sensitivity of the sensor and FWHM, an important parameter to describe the detection accuracy, is the full width at half-maximum of the resonant peaks.

The schematic of the proposed PCF-SPR sensor is shown in Fig. 2. The supercontinuum broadband source (SBS) is used as the light source